

FLOW RATE ANALYSES AND CALIBRATIONS OF KEROSENE CRACKING FOR SUPERSONIC COMBUSTION

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Nomenclatures

A	=	cross section area of heating tube
A^*	=	throat area of sonic nozzle
a	=	constant in nominal mole fraction of gaseous products
ECS	=	extended corresponding states
IGM	=	ideal gas mixture
k	=	rate constant of kerosene thermal cracking
L	=	total length of heating tube
m_g	=	mass of gaseous products collected after cooling from kerosene cracking
m_L	=	mass of liquid products collected after cooling from kerosene cracking
N_g	=	mole numbers of gaseous products
N_k	=	mole numbers of equivalent unreacted kerosene
N_{res}	=	mole numbers of residuals
N_0	=	total mole numbers of cold kerosene fed
p	=	fuel pressure
q	=	mass flow rate
\hat{R}	=	universal gas constant
R_k	=	gas constant of unreacted kerosene
T	=	fuel temperature
T_1	=	Characteristic temperature for kerosene thermal cracking
t	=	time
u	=	cracked kerosene velocity inside heater
α	=	growth constant in nominal mole fraction of gaseous products
β	=	v_g/v_{res}
χ_g	=	mole fraction of gaseous products
χ_g^*	=	nominal mole fraction of gaseous products
γ	=	ratio of specific heats for cracked kerosene mixture
ρ	=	density for cracked kerosene mixture
τ	=	residence time of kerosene inside heater
τ_k	=	residence time of unreacted kerosene inside heater
$\bar{\mu}$	=	average molecular weight of cracked kerosene mixture
μ_g	=	average molecular weight of gaseous products
μ_k	=	average molecular weight of unreacted kerosene
μ_L	=	average molecular weight of liquid products
μ_{res}	=	average molecular weight of residuals
v_g	=	stoichiometric coefficients of gaseous products in the one-step kerosene cracking model
v_{res}	=	stoichiometric coefficients of residuals in the one-step kerosene cracking model

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Abstract

Measurements of kerosene conversion due to thermal cracking and mass flow rate through a sonic nozzle have been made under supercritical conditions. Based on the temperature dependency of mole fraction of gaseous products from kerosene cracking, a one-step cracking model has been proposed to correlate the kerosene conversion and the mass flow rate through a sonic nozzle. In this model, the cracked kerosene was described as a three-component ideal gas mixture (IGM) of unreacted kerosene, gaseous products after cooled to room temperature and residuals. The composition of unreacted kerosene and gaseous products were determined by a gas chromatography, while the approximate chemical formula of the residuals was derived from the average molecular weight of cracked kerosene mixture at high temperature. The mass flow rate of cracked kerosene was then calculated from ideal gas law for the three-component mixture. Agreement was obtained when comparing the calculated mass flow rate with the measurements. Kerosene residence time and the rate constant of conversion inside a heater were also discussed based on this global cracking model.

Introduction

Hydrocarbon fuels have been considered as the primary cooling media in hypersonic vehicles. The fuel temperature would rapidly exceed the cracking limits ($\sim 750\text{K}$) for high Mach number ($M > 6$) flights, where thermal cracking are occurring. The bonds of large molecules are broken to form smaller molecules and the fuel density decreases dramatically. The fuel mass flow rate per unit area also decreases an order of magnitude from room temperature to where thermal cracking occurs. An optimized fuel heating and injection system needs to account for this changes in fuel flow rates. Nevertheless, a cracked fuel system would contain hundreds of species and thousands of chemical reactions, which makes the prediction and control of fuel flow rate very complicated.

For supercritical kerosene, measurements of mass flow rate using a sonic nozzle have been proposed in our early studies [1]. It has been demonstrated that the flow rates can be theoretically predicted up to the cracking limit ($\sim 750\text{K}$). For partially cracked kerosene, the computed mass flow rates can no longer be used because the fuel composition is dramatically changed. However, the mass flow rate through a sonic nozzle of cracked fuel could still be determined theoretically if the accurate variations of fuel compositions on temperature and pressure were known. However, the cracked fuel mixture would undergo phase changes when cooled down to the room temperature. The unreacted kerosene and the heavier cracking products ($>C_3$) condensed to liquid products, while the lightweight products (C_1-C_5) turned into gaseous products. The compositions and mole fractions of cracked products could be analyzed experimentally. For application purpose, the question is: could the mass flow rate of cracked fuel be determined directly from these measured compositions of cracked products? The answer is questionable. The reason is that not only the phases of cracked products but also their compositions would in general vary when cooled down to room temperature. For example, it is very likely that some small radicals or molecule fragments could exist in the high temperature cracked mixture but would be absorbed into liquid products or turn into gaseous products after cooling. The existence of small radicals would significantly reduce the average molecular weight and therefore the mass flow rate of cracked fuel mixture through a sonic nozzle. It is desirable that some reaction mechanisms can be used to determine the actual compositions of cracked fuel. However, to date, the thermal cracking mechanism of hydrocarbon fuels are still in wide debate. How thermal cracking would affect the fuel flow rate is left unclear.

In this study, based on measurements of flow rates and total conversion of China No.3 kerosene, a one-step global model has been proposed to describe the overall thermal cracking under supercritical conditions. High temperature cracked fuel is lumped into unreacted kerosene, gaseous products after cooling, and residuals including various radicals or molecule fragments. The correlation of the mass flow rate and the total conversion for a given heater configuration is then derived from this lumped model. Residence time of kerosene and the rate constant of conversion inside the heater were also analyzed and reasonable results have been obtained.

Experimental

Kerosene Heating System

A major concern in design of the kerosene heating system is how to reduce the carbon formation, particularly due to pyrolytic cracking. The rate of this fuel coking is generally proportional exponentially to temperature

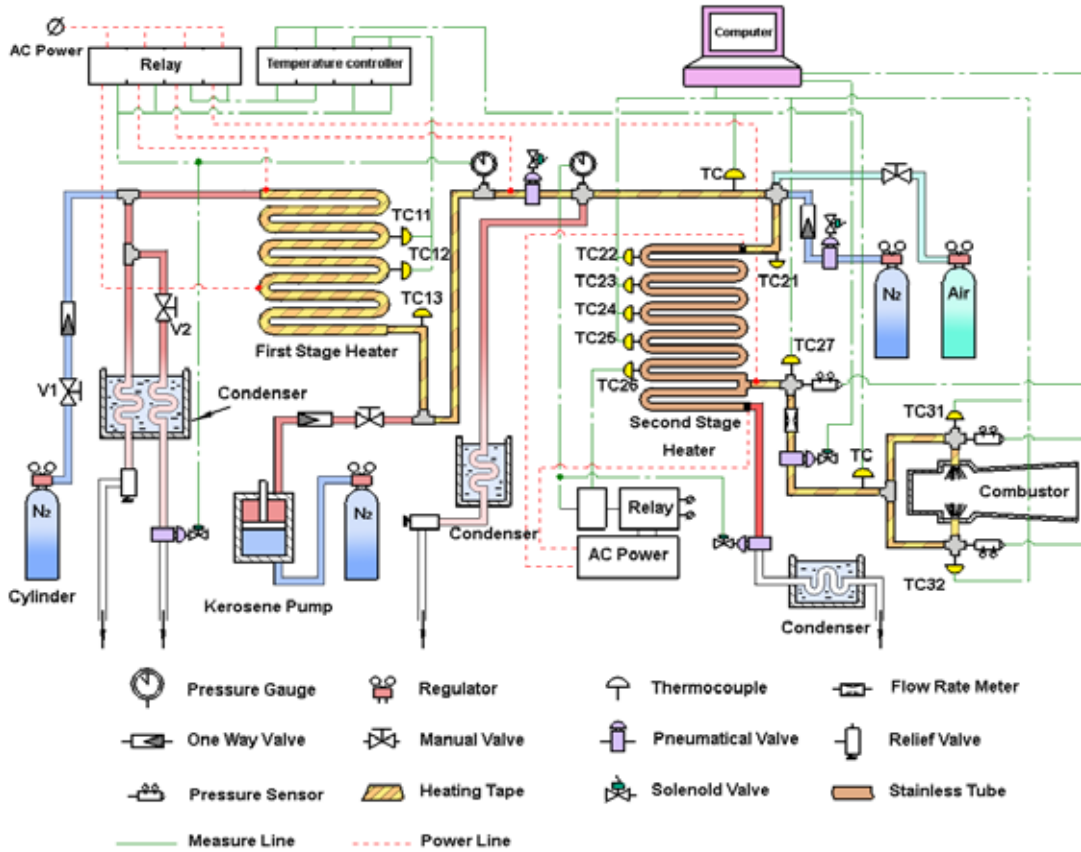


Figure 1 Schematic diagram of kerosene delivery and heating system.

and linearly to the residence time [2]. To minimize the fuel coking at high temperature, a two-stage heating system has been designed to be operated at supercritical conditions as shown in Fig. 1. The first stage was a storage type heater that can heat kerosene of 0.8 kg up to 570 K within a relative longer heating time (typically 20 minutes) with minor/negligible coking deposits; the second stage was a flow reactor type heater, which was capable of rapidly heating kerosene up to 920 K or higher as fuel passing through it. The residence time of kerosene within the second heater was very short, typically 1-4 seconds.

The first-stage heater consisted of a twenty-meter long stainless steel tube of 20 mm outer diameter and 1.5 mm wall thickness, which was wound into a cylinder of 30 cm in diameter. The stainless steel tube was wrapped with five 960-W heating tapes, which was controlled independently in order to achieve a uniform temperature distribution along the tube. Two types of heater have been used for the second stage heater: Type-A heater was made of a hollow stainless steel tube of 16 mm outer diameter and 2 mm wall thickness; the Type-B heater used the same dimension tube but filled with five stainless steel tubes of 4 mm outer diameter and 1 mm wall thickness as shown in figure 2. The total lengths of heating tubes were approximately 23.5 m. To rapidly raise the temperature, the second heater was heated electrically by directly passing a current through the stainless steel tube at 80-100 DC voltages from a pulsed AC/DC welder power supply of 250 KW.

Two pneumatic valves (Swagelok, model No. SS6UM) were employed to turn on/off the two heaters, as shown in Fig. 1. After each run, nitrogen and air were used to purge the residual kerosene inside the second-stage heater and to

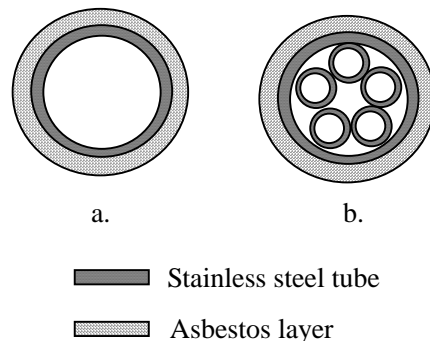


Figure 2. Two types of tubes used for the second heater.

reduce the accumulations of carbon deposits. Two groups of K-type thermocouples, TC11-13 and TC21-26 in Fig. 1, were spot-welded to the out surface of the heater tubes to monitor and achieve the feedback control of fuel temperature distribution along the heating tubes.

Table 1. Test conditions

Heater type	Sonic nozzle, mm	Fuel pressure, atm	Fuel temperature, K	Fuel flow rate, g/s
Type A, B	2.15, 2.5, 3.08, 3.4	30-50	700-920	20-80

Flow Rate Calibration System

The mass flow rate of cracked kerosene was measured using a sonic nozzle installed at the exit of the second heater. After passing through the sonic nozzle, the cracked fuel mixture was cooled to room temperature using a condenser from an air-conditioner circulated with cold water. The liquid products and carbon deposits were collected directly after cooling, while the gaseous products were collected using a container immersed in a water pool and its volume was measured by the volume of water displaced. The composition of gaseous product was analyzed using a gas chromatography, and the average molecular weight and the density were determined. The mass flow rates were obtained by the total mass of liquid and gaseous products collected divided by the time duration of fuel discharging.

Due to the large variation in kerosene density for the temperature range of 570K-920K, four different throat diameters i.e., 2.15mm, 2.5mm, 3.08mm and 3.4mm were used to meet the flow rate requirements for further combustion experiments. A schematic diagram of the flow calibration system is shown in Fig.3. The test conditions are summarized in table 1. A noticeable feature in the present study is the large volume of fuel flow rate being used.

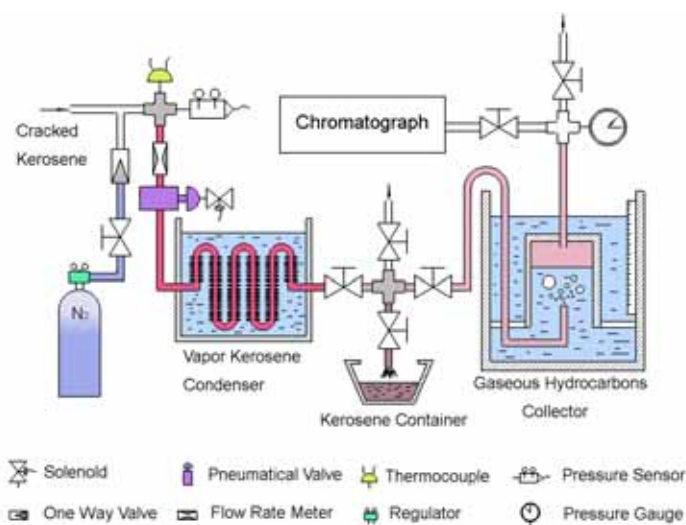


Figure 3 Schematic diagram for kerosene flow rate measurement system.

Table 2. Average molecular weight of gaseous products from China No. 3 kerosene thermal cracking

Temperature, K	820	870	900	920
Molecular weight	30.9	27.4	28.6	28.1

Compositions of Kerosene and Its Cracked Products

China NO.3 kerosene was chosen in this study. China No.3 kerosene is a conventional jet fuel. On the volume basis, it is approximately composed of 92.5% saturated hydrocarbons, 0.5% unsaturated hydrocarbons, and 7% aromatic hydrocarbons. Samples of China No.3 kerosene were further analyzed using a gas chromatography. Figure 4 shows the compound mass fraction by carbon number. The overall chemical formula of China No.3 is approximately $C_{11}H_{22}$. Based on the composition analyses of kerosenes, their thermophysical properties can be simulated using NIST SUPTRAPP program [1,3].

When cooled to ambient condition, the cracked products of kerosene mainly include liquid and gaseous products. The liquid products collected also contain carbon deposits from coking and some tar-like materials. The detailed compositions of the liquid products are very complex and will be analyzed in the near future. The primary gaseous products obtained are low molecular number (C1-C5) alkanes and alkenes. Surprisingly, no hydrogen was detected in the experiments, which might ascribe to the use of supercritical pressures and very long heating tubes in the experiments. Figure 5 shows the compositions of gaseous products collected at different temperatures. Its average molecular weights are shown in table 2, which were roughly 28.8 on

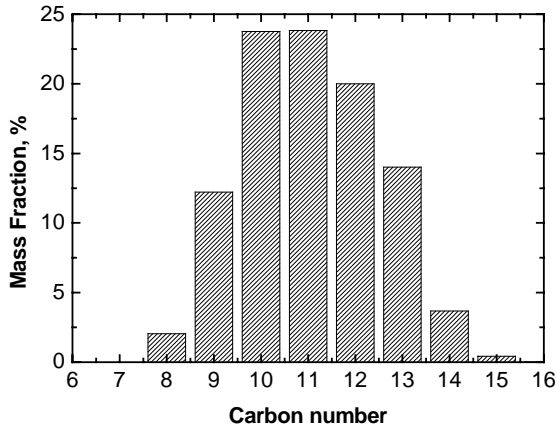


Figure 4 Compositions of China No. 3 kerosene

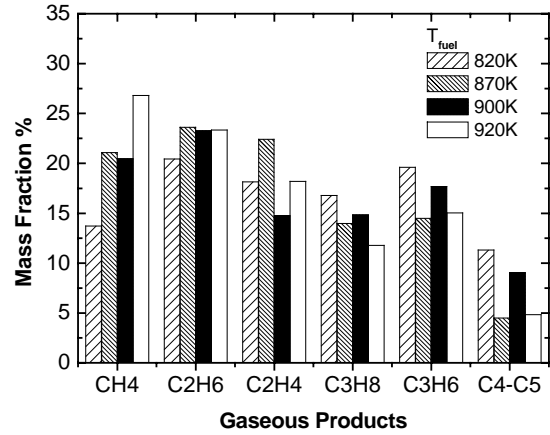


Figure 5 Compositions of gaseous products from China No. 3 kerosene thermal cracking.

average. The chemical formula of gaseous product mixture can be approximated by $C_{1.96}H_{5.28}$.

Kerosene Conversion and Mass Flow Rate

Because kerosene is a mixture of different hydrocarbons, it is very difficult to define experimentally the actual percentage of kerosene cracked. Edwards and Anderson defined a fuel conversion to gas over a certain period of time based on the liquid volume change [4]. In the present experiments, the total mass of liquid products m_L and the total mass of gaseous products m_g have been measured. If all of the liquid products are treated as unreacted kerosene, a nominal mole fraction of gaseous products can be defined as

$$\chi'_g = \frac{m_g / \mu_g}{m_g / \mu_g + m_L / \mu_k} \quad (1)$$

Where μ_k and μ_g are the average molecular weight of unreacted kerosene and gaseous products, respectively. The collected liquid products could be further divided into two groups: the ones which could be further cracked were lumped into the unreacted kerosene with a total mole number of N_k ; the others which could no longer be cracked lumped into a group called residuals with a total mole number of N_{res} . Equation. (1) can be written as

$$\chi'_g = \frac{1}{1 + (N_k + N_{res})\mu_L / N_g \mu_k} \quad (2)$$

where N_g is the total mole number of gaseous products and

$$\mu_L = \frac{\mu_{res} / \mu_k + N_k / N_{res}}{1 + N_k / N_{res}} \mu_k \quad (3)$$

is the average molecular weight of liquid products.

The temperature dependencies of χ'_g were determined experimentally. Figure 6 shows the measured χ'_g as a function of fuel temperature for China No. 3 kerosene after passing through type A and B heaters. It has been found that this nominal mole fraction generally has the following form

$$\chi'_g = \frac{1}{1 + a + e^{-\alpha(T-T_1)}} \quad (4)$$

Where the parameters α and T_1 are functions of heater configurations. The experimental data appeared to be independent on or only a weak function of fuel pressure and throat diameters of

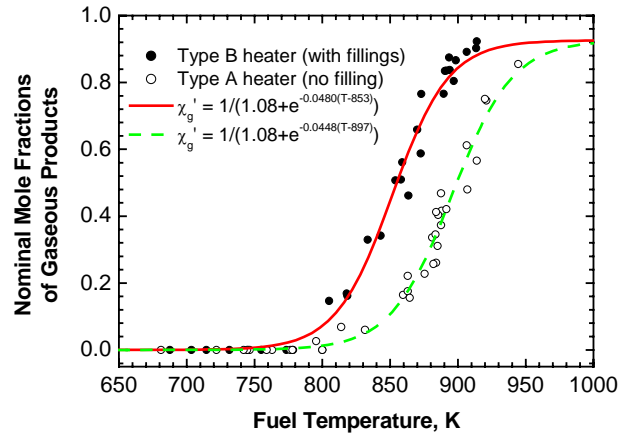


Figure 6 Nominal mole fractions of gaseous products as function of temperature for China No. 3 kerosene after passing through two types of heaters.

sonic nozzles. Since N_k as defined should go to zero as temperature became very large, from equation (2),

$$a = \lim_{T \rightarrow \infty} \frac{N_{res} \mu_{res}}{N_g \mu_k} \quad (5)$$

Furthermore, the total mass is conserved. If the total number of kerosene fed is N_0 , then

$$N_0 \mu_k = N_k \mu_k + N_{res} \mu_{res} + N_g \mu_g \quad (6)$$

From (2)-(4) and (6), it can be solved that

$$\frac{N_g}{N_0} = \frac{\mu_k}{\mu_g + \mu_k (a + e^{-\alpha(T-T_1)})} \quad (7)$$

The actual mole fraction of gaseous products is defined as

$$\chi_g = \frac{1}{1 + (N_k + N_{res}) / N_g} \quad (8)$$

From (2) and (4), it can be written as

$$\chi_g = \frac{1}{1 + \mu_k / \mu_L (a + e^{-\alpha(T-T_1)})} \quad (9)$$

The average molecular weight of the cracked fuel mixture can then be calculated as

$$\bar{\mu} = \chi_g \mu_g + (1 - \chi_g) \mu_L = \frac{\mu_g + \mu_k (a + e^{-\alpha(T-T_1)})}{1 + \mu_k / \mu_L (a + e^{-\alpha(T-T_1)})} \quad (10)$$

It will be seen later that for temperature higher than the cracking limit ($\sim 750\text{K}$), the cracked kerosene can be treated as a mixture of ideal gases with negligible discrepancy. If the dependency of $\bar{\mu}_L$ on the fuel temperature is known, then from the average molecular weight (10) and the ideal gas law, the mass flow rate of cracked fuel mixture through a sonic nozzle can be calculated as

$$q = \frac{pA^*}{\sqrt{\hat{R}T / \bar{\mu}}} f(\gamma) \quad (11)$$

where A^* is the throat diameter of the sonic nozzle, and

$$f(\gamma) = \sqrt{\gamma \left(\frac{2}{1+\gamma} \right)^{(\gamma+1)/(\gamma-1)}} \quad (12)$$

Because the degrees of freedom of the unreacted kerosene and mixture of its cracking products are very large, $f(\gamma)$ is relatively constant during cracking and was approximated by 0.65. When comparing the calculated and measured mass flow rate of kerosene, a discharge coefficient of 0.91 has been used throughout the text for all sonic nozzles.

Figure 7 shows the temperature dependency of measured mass flow rate per unit throat area after passing through the type-A heater at pressures converted to 35atm. When applying the relation (11) to the measured flow rate as temperature approaches 1000K, where the conversion of kerosene is nearly complete and dominate parts of the mixture is the gaseous products, it has been found that the average molecular weight of cracked kerosene $\bar{\mu}$ go to approximately 17, which is much lower than the average molecular weight of collected gaseous products (~ 28.8). Noticing that $\bar{\mu}$ in (11) is the average molecular weight measured at the sonic nozzle, where the fuel temperature is very high, the small value of $\bar{\mu}$ indicates that there are large amount of low molecular weight species existing in the cracked fuel mixture. Due to the lightweight nature in

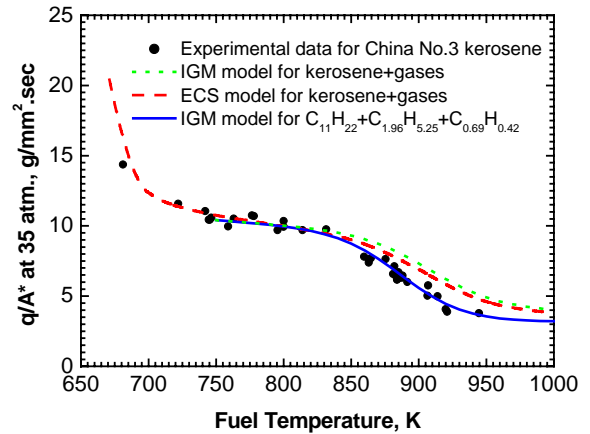


Figure 7 Comparison of flow rate measurements and calculations based on three different models for China No .3 kerosene and type A heater.

mass, it should be a mixture of free radicals and molecule fragments, such as H, CH, etc., which could exist at high temperature but would be absorbed into the liquids after cooled down to the ambient temperature. The average chemical formula of the mixture of these species will be determined later.

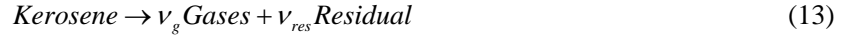
Figure 7 also gives the comparison the mass flow rate calculated based on the model of extended corresponding states (ECS) [3] and the model of ideal gas mixture (IGM). In both cases, the cracked fuel mixture was represented by a blend of two surrogates: one surrogate for unreacted kerosene and one surrogate for the collected gaseous products. The surrogate for unreacted kerosene was similar to the model developed in our earlier investigation [1] based the surrogate proposed by Dagaut [5], but modified here to more accurately simulate the actual molecular weight and C/H ratio of China No.3 kerosene. The surrogate of gaseous products was composed of five main elements from figure 5. The compositions of two surrogates are listed in table 3. The mole fractions of gaseous products in the blend were determined from the experimental data in figure 6 but with $a = 0$. Figure 7 shows that for temperature higher than about 750K, both ECS and IGM models gave very close flow rate predictions, which confirms that the cracked kerosene can be indeed approximated by model of ideal gas mixture. However, both calculations gave a much large flow rates than the measurements indicating a third part was missing. The third curve (solid line) in the figure will be explained later.

Table 3. Surrogate compositions (Mole fractions) for China No.3 kerosene and its gaseous products of thermal cracking

Surrogate for China No.3 kerosene		Surrogate for gaseous products	
N-Dodecane	0.63	CH ₄	0.35
1,3,5-trimethylcyclohexane	0.30	C ₂ H ₆	0.20
N-propylbenzene	0.07	C ₃ H ₈	0.15
		C ₂ H ₄	0.15
		C ₃ H ₆	0.15
Average molecular weight	152		28.7
Average chemical formula	C _{10.9} H _{21.3}		C _{1.95} H _{5.3}

A One-Step Thermal Cracking Model

To account for the effect of missing third part in cracked kerosene, a one-step model of kerosene cracking has been proposed, which is described as following



As a first order approximation, the conversion of kerosene can be modeled as

$$\frac{N_k}{N_0} = e^{-kt} \quad (14)$$

Where the cracking rate constant k is generally a function of fuel pressure and temperature. From (13) and (14), the mole numbers of gaseous products and residuals are

$$N_g = v_g N_0 (1 - e^{-kt}) \quad (15)$$

$$N_{res} = v_{res} N_0 (1 - e^{-kt}) \quad (16)$$

Also, it follows that

$$a = \frac{v_{res} \mu_{res}}{v_g \mu_k} \quad (17)$$

Mass conservation (13) gives

$$\mu_k = v_g \mu_g + v_c \mu_c \quad (18)$$

From (14) -(16),

$$N_g / N_0 = v_g (1 - e^{-kt}) \quad (19)$$

$$N_k / N_{res} = \frac{1}{v_{res}} \left(\frac{1}{1 - e^{-kt}} - 1 \right) = \frac{1}{v_{res}} \left(\frac{v_g N_0}{N_g} - 1 \right) \quad (20)$$

Substitution of (7) into (20) and using (17) and (18) gives

$$N_k / N_{res} = \frac{1}{v_{res}} \left(\frac{v_g N_0}{N_g} - 1 \right) = \frac{v_g}{v_{res}} e^{-\alpha(T-T_1)} \quad (21)$$

Therefore the average molecular weight of the liquid products is

$$\mu_L = \frac{\mu_{res} / \mu_k + \beta e^{-\alpha(T-T_1)}}{1 + \beta e^{-\alpha(T-T_1)}} \mu_k \quad (22)$$

where

$$\beta = \frac{v_g}{v_{res}} \quad (23)$$

The determination of the approximate chemical formula of the residual is following: from the conversion measurements in figure 6, the constant a can be determined, thus

$$\mu_{res} / \beta = a \mu_k \quad (24)$$

From the limit values of flow rate measured at high temperature ($\sim 1000\text{K}$) in figure 7 and ideal gas law (11), the average molecular weight of cracked kerosene $\bar{\mu}$ at high temperature can be calculated. By taking the high temperature limit of (10), it can be solved that

$$\frac{1}{\beta} = \frac{\mu_k + \mu_{res} / \beta}{\bar{\mu}} - 1 \quad (25)$$

From (24) and (25), β and v_{res} can be determined. Assuming the average chemical formula of residuals is $C_x H_y$, then

$$12x + y = \mu_{res} \quad (26)$$

If use $C_{11}H_{22}$ for kerosene and $C_{1.96}H_{5.28}$ for gaseous products, from (13), we have

$$2x - y = 1.36\beta \quad (27)$$

Solving equations (26) and (27), x and y can be obtained. The results for type A and B heater were summarized in table 4.

Using calculated parameters, the mass flow rates of cracked kerosene were calculated and plotted in figure 7 (type A) and figure 8 (type B). It can be seen from the figures this three-component model gave satisfactory predictions for the mass flow rate. Results from calculations based on IGM and ECS models similar to that in figure 7 were also plotted in figure 8.

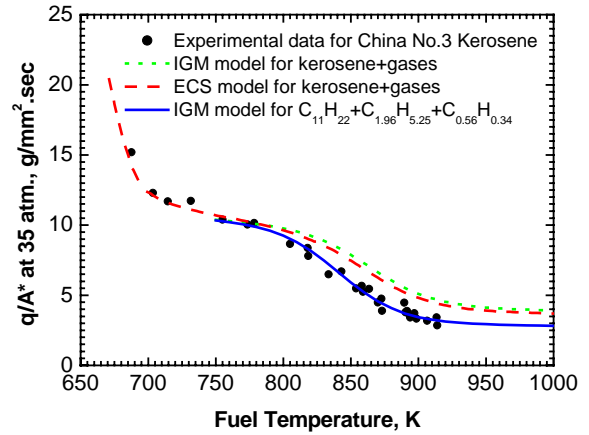


Figure 8 Comparison of flow rate measurements and calculations based on three different models for China No. 3 kerosene and type B heater.

Table 4. Parameters of residuals for two types of heaters

	a	$\bar{\mu}$	β	μ_{res}	v_g	v_{res}	x	y
Heater A	0.08	17	0.704	8.68	3.74	5.31	0.69	0.42
Heater B	0.08	15	0.574	7.07	3.75	6.53	0.56	0.34

Fuel Residence Time inside Heater

It is very interesting to figure out the residence time of kerosene inside the heater. For this purpose, the same model of ideal gas mixture has been employed. The average molecular weight of cracked kerosene can be modeled as

$$\bar{\mu} = \frac{N_0 \mu_k}{N_k + N_g + N_{res}} \quad (28)$$

By use of (14)-(16), it can be written as

$$\bar{\mu} = \frac{\mu_k}{v_g + v_{res} + (1 - v_g - v_{res})e^{-kt}} \quad (29)$$

The mass flow rate inside the heating tube is

$$q = \rho u A = \frac{p u A \bar{\mu}}{\hat{R} T} \quad (30)$$

From which the average velocity at time t is

$$u = \frac{q \hat{R} T}{P A \bar{\mu}} \quad (31)$$

It is anticipated that the fuel flow is going to accelerate as kerosene cracking into small molecules. If the total length of the heating tube is L and the pressure and temperature inside the tube are assumed to be constant, then

$$L = \int_0^\tau u dt = \frac{q \hat{R} T}{P A} \int_0^\tau \frac{dt}{\bar{\mu}} \quad (32)$$

Substitution of (28) into (32) we obtained

$$1 - e^{-k\tau} = \frac{1}{1 - v_g - v_{res}} k (\tau_0 - (v_g + v_{res})\tau) \quad (33)$$

Where

$$\tau_0 = \frac{p A L}{q R_k T} \quad (34)$$

By use of (11), we have,

$$\tau_0 = \sqrt{\frac{\mu_k}{\bar{\mu}}} \tau_k \quad (35)$$

where

$$\tau_k = \frac{A L}{A^* f(\gamma) \sqrt{R_k T}} \quad (36)$$

Because f(γ) is relatively constant during cracking, τ_k is approximately equal to the residence time of unreacted kerosene inside heater. Solving (7) and (15) for kτ, substituting into (33) and using relations (17) and (18) gives

$$k = \frac{1}{\tau_0} \left(\frac{1 - v_g - v_{res}}{1 + v_g e^{-\alpha(T-T_1)}} + (v_g + v_{res}) \ln \left(1 + \frac{1}{v_g} e^{\alpha(T-T_1)} \right) \right) \quad (37)$$

It is a bit surprising that the overall rate constant of kerosene cracking can be determined explicitly from the measurements of nominal mole fraction of gaseous products (4). Note that 1/k has the dimension of time and is of the order of kerosene lifetime. Figure 9 shows the calculated kerosene lifetime in type A heating tube as a function of temperature. It can be seen that the lifetime is very long at low temperatures and decreases to about 1 sec at about 960 K. These results are comparable to the dodecane half-life up to about 1000 K in [6] calculated by use of a detailed cracking mechanism. For temperature above 1000 K, further cracking of small molecules should be taken into account. However, current results were obtained using a very simple model.

When k is computed, the residence time of kerosene inside heater can be solved from nonlinear equation (33). The results are shown in figure 10. The

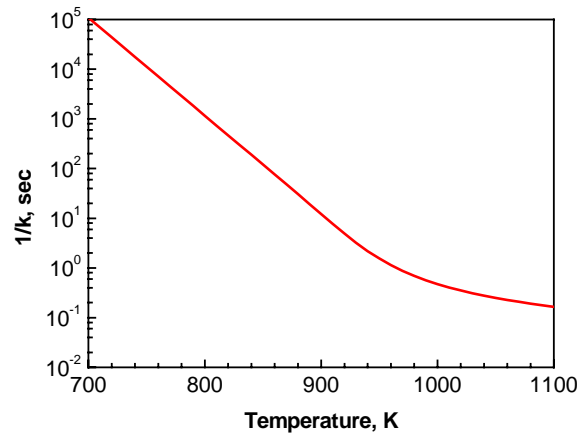


Figure 9 Kerosene lifetimes in type A heater as a function of temperature.

residence time is shown to deviate from the value of unreacted kerosene as cracking occurs. It decreased roughly from 4 sec at 800 K to 1.5 sec at 1000 K. This calculated residence time could be used to determine the optimum time delay between two pneumatic valves in figure 1 such that a relatively constant fuel pressure could be reached for combustion tests.

Conclusion

Measurements of kerosene conversion and mass flow rate through a sonic nozzle have been made at supercritical conditions. A one-step cracking model has been developed to correlate the kerosene conversion and the mass flow rate. In this model, the cracked kerosene mixture is lumped into unreacted kerosene, gaseous products and residuals. It has been demonstrated that, a residuals of small radicals or molecule fragments was required to accurately predict the mass flow rate of cracked kerosene. The equivalent chemical formulas of the residuals have been determined for two type of heater. The method proposed in this study could be virtually applied to any heater. The possibility of existence of large amount of small radical in the cracked fuel mixture at high temperatures draws the attention to refine the cracking mechanisms of hydrocarbon fuels. Its effects on ignition and combustion of kerosene are yet to be determined.

Kerosene residence time and the rate constant of conversion inside the heater were also discussed based on the lumped model. Reasonable results regarding the overall rate constant or lifetime of kerosene cracking has been obtained.

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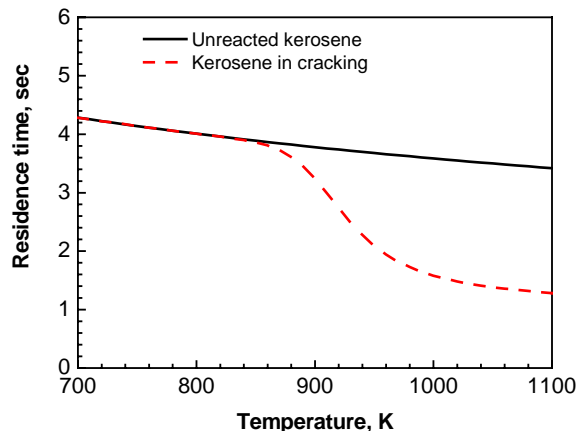


Figure 10 Comparisons of the residence times as functions of temperature for unreacted and cracking kerosene in type A heater.